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DETERMINATION OF DYNAMIC TENSILE STRENGTH OF METALS FROM JET BREAK-UP STUDIES

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In the present studies the dynamic tensile strength of aluminum, copper and mild steel is calculated from the experimental determination of the velocity and length of different particles of the particulated metal jets. The conical cavities in metal discs are collapsed by shock wave impact to produce jets. Because of the velocity gradient between its tip and tail end, the jet deforms plastically until it breaks into a series of particles. The jet elongation and break-up is recorded using Synchro-Streak Technique and Flash Radiography. It is observed that the jet breaks into particles of smaller length when stretched under higher strain rates. The angle of the collapsed cavity was changed to produce the jets stretching under strain rates of 10^4 to 10^5 s^{-1}. The average dynamic tensile rupture strength of aluminum, copper and mild steel has been calculated to be 500, 1100 and 1850 Mpa, respectively, which is roughly 4–5 times their quasi-static tensile strength.

INTRODUCTION

The strength properties of materials at high strain rate are needed in determining the response of structures to the dynamic loading, associated with the shock and impact loading processes. It is well known that the yield strength and the ultimate tensile strength of materials are determined by the behavior of dislocations, and these depend on both the pre-history of loading and strain rate. For fcc metals, at low strain rates, the true stress increases linearly with the logarithm of strain rate. At high strain rates, exceeding $10^3 s^{-1}$, the true stress increases approximately linearly with strain rate. These experimental observations have been explained on the basis of transitions in the rate controlling deformation mechanism with increasing strain rates [1]. At the low strain rates, thermal activation is required to assist a dislocation to cross the barriers. However, at the high strain rates, the continuous motion of dislocation moving through a lattice is resisted by lattice potential itself, as well as, by the interactions with the phonons, electrons and radiations. These dissipative processes are viscous in nature and lead to a linear dependence of the flow stress on the applied strain rate. Therefore, with the increase in strain rate, the plastic flow of metals changes from a thermal activation to the one with viscous drag.

There are different ways of estimating the dynamic tensile strength of metals. The rupture strength of metals at high strain rates can be determined from the measurements

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of length and velocity [2] of the different particles of the broken jets. In the second method [3], the metal jet is made to impact on to the target metal to make a crater. Then the dynamic yield strength of target metal can be calculated from the measurements of crater radius, jet radius and jet velocity along with the densities of jet and target metals. The dynamic tensile strength of the metals can also be calculated from the mechanical equation of state of the metals. The strain, strain rate and the temperature of deformation process must be known for this calculation.

In the present studies, the dynamic tensile rupture strength of aluminium, mild steel and copper is calculated from the experimental data of velocity and length of different pieces of the particulated jets.

RUPTURE STRENGTH OF METALS FROM JET BREAK-UP

The metal jets formed by shaped charge mechanism [4] or shock induced cavity collapse [5] have very high velocity gradient between tip and tail ends. The jet deforms plastically under influence of high velocity gradient. In tensile deformation, the necking is usually a precursor to ductile fracture. The process of neck formation in aluminum jet, prior to fracture and break-up is shown in “Fig. 1”.

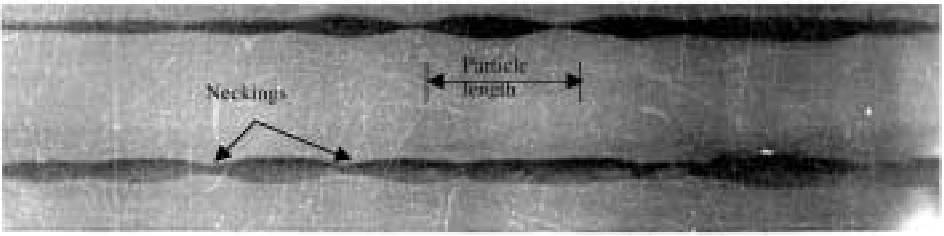

Figure 1: Neck formation in an aluminium jet prior to jet break-up. The jet with a tip velocity 5.4 mm/μs and stretching under strain rate of 10^4 s^{-1} was recorded by a streak camera after traveling 80 cm from the point of formation.

Neck formation commences at or near the point of maximum load, i.e., $P = P_{max}$. In the absence of work hardening, necking would commence immediately after the metal yields stress. However, work hardening raises the yield stress and stabilizes the plastic flow. When the increase in stress due to the decrease in the cross-sectional area exceeds that due to work hardening, an unstable condition exists and necking begins.
The load at any point can be written as

$$P = \sigma A \tag{1}$$

where σ is true stress and A is the instantaneous cross-sectional area of the jet. At the maximum load point

$$dP = A d\sigma + \sigma dA = 0 \tag{2}$$

Assuming that the volume v of specimen does not change during deformation

$$dv = d\left[A(1+e)l_O\right] = 0 \tag{3}$$

where $A_O = A(l+e)$ is the initial and A is current cross-sectional area, l_o the initial length of the jet and e is the conventional strain. Eliminating dA in eq. (2) and eq. (3), the condition of maximum load can be written as

$$d\sigma = \frac{\sigma de}{1+e} = \sigma d\varepsilon \quad \text{or} \quad \frac{d\sigma}{d\varepsilon} = \sigma \tag{4}$$

where ε = ln (1+e) is the natural strain. Consequently, necking will take place at a strain where the slope of the true stress-strain curve equals the true stress at that strain. On further stretching, the jet will break into individual pieces of length l_i.

The computation of the metal strength is based on three assumptions. First: the jet is ruptured into pieces of maximum length l_i with kinetic energy of the individual pieces E_i, in a center of mass system, not exceeding the work due to tension, W, up to the ultimate strength, i.e. $E_i \le W$. Second: there is linear velocity gradient along the jet. The jet is broken into pieces of length l_i, with approximately equal inter-particle velocity difference Δv, i.e.

$$\Delta v \cong \frac{dV}{dl} l_i \quad . \tag{5}$$

Third: the jet fragmentation is brittle and the work of deformation of jet material up to ultimate strength σ_f is determined by the expression

$$W = \frac{\sigma_f^{\,2}}{2E\rho} \tag{6}$$

where ρ and E are the density and Young's Modulus of the jet material.

The average kinetic energy E of the jet can be written [6] as

$$E = \frac{1}{2} M V_c^2 + \frac{1}{24} M \Delta V^2 \tag{7}$$

where V_c is the velocity of centre of mass of the jet and ΔV is the velocity difference (V_j–V_0) between tip and tail ends. If V_c and ΔV are nearly the same then roughly 8% of the kinetic energy of the jet, relative to centre of mass of the jet, is available to stretch the jet. Once the jet breaks into n particles, the energy associated with each particle, $(M\,\Delta V^2) / (24\,n^2)$, falls off rapidly and no more stretching occurs in individual particles. Specific kinetic energy of longitudinal relative motion of each piece E_i is written as $(\Delta v)^2/24$, where $\Delta v = \Delta V/n$.

From assumption 1 it follows that

$$\frac{(\Delta v)^2}{24} \le \frac{\sigma_f^{\,2}}{2E\rho} \quad . \tag{8}$$

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Putting the value of Δv from eq. (5)

$$\sigma_f \geq \sqrt{\frac{E\rho}{12}} \left({}^{dV}\!/_{dl} \right) . l_i \ . \qquad (9)$$

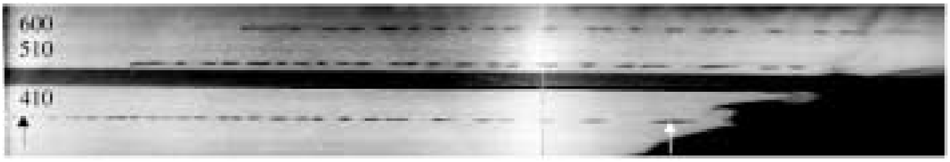
The velocity gradient dV/dl or the strain rate decreases with the stretching in the jet. At the time of jet break-up it can be written as $\dot{\varepsilon}_b$, the strain rate at break-up. Equation (9) can be rewritten as

$$\sigma_f \geq \sqrt{\frac{E\rho}{12}} \, \dot{\varepsilon}_b \, l_i \ . \qquad (10)$$

Evidently from eq. (10), the strength of jet material σ_f under tension at high strain rate can be determined from the measurements of strain rate and the average length l_i of the jet particles at break-up.

EXPERIMENTS FOR PARTICLE SIZE MEASUREMENTS

Experiments were conducted in which the conical cavities in aluminum, copper and mild steel discs were collapsed by shock wave impact to form the jets. The jet elongation and particulation was recorded by Synchro-Streak Technique [7] and in some cases by Flash Radiography. The particulated copper jet recorded by Synchro-Streak Technique at three stand-off distances of 410, 510 and 610 mm from the cavity apex is shown in "Fig. 2". The jet with the initial strain rate of 3.8 x10^4 s^{-1} was formed by shock collapsing a conical cavity of half angle 30°. Particulated aluminum jet recorded at 700 and 860 mm stand-off distances is shown in "Fig. 3". The jet with initial strain rate of 2.7x$10^4 s^{-1}$ was formed by the collapse of conical cavity of half angle 45°. This jet is particulated and 32 particles are clearly visible in the camera record.



5.25 km/s (tip) 2.51 km/s (tail)

Figure 2: Particulated copper jet formed by conical cavity of half angle 30°, recorded at three stand-off distances of 410, 510 and 610 mm.

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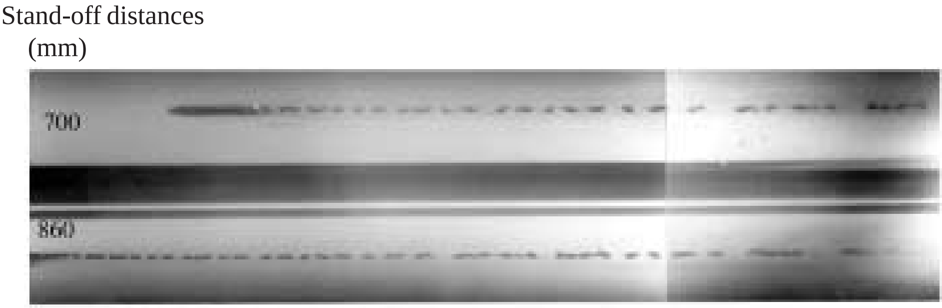

Figure 3: Particulated aluminium jet recorded by Synchro-Streak Technique. The jet, stretching under strain rate of 2.7x $10^4 s^{-1}$, has been particulated into 32 particles.

The jet particles pass across the camera slit at two or three observation points. From the measurements of arrival time of different particles at two observation points, the velocity of each particle is calculated from the expression

$$V_i = \frac{s_2 - s_1}{t_{i2} - t_{i1}} \tag{11}$$

where V_i is the velocity of i^{th} particle, t_{i1} and t_{i2} are the arrival times of the centre of mass of i^{th} particle at first and second observation point and s_1 and s_2 are the stand-off distances of the first and the second observation points, respectively. Particles length has also been measured from the same camera record by using equation

$$l_i = \left(\frac{X_i}{U_{wr}} \right) V_i \tag{12}$$

where X_i is the particle length measured on the film plane, U_{wr} is the camera writing rate. Here (X_i / U_{wr}) is the time of passage of the i^{th} particle across the camera slit. The velocity and the length of all the particles have been measured to calculate the cumulative jet length and the strain rate at break-up.

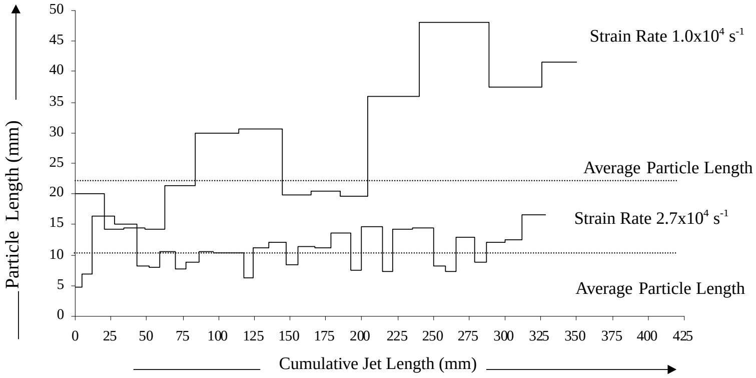

Figure 4: The distribution of particles lengths in the two aluminium jets, stretching under strain rates of 1x 10^4 s^{-1} and 2.7x 10^4 s^{-1}, respectively.

RESULTS AND DISCUSSION

The jet break-up is a strain rate sensitive process. The distribution of particles length in two aluminium jets stretching under strain rates of 1x 10^4 s^{-1} and 2.7x 10^4 s^{-1} is shown in “Fig. 4”. Particles are randomly distributed in terms of their length with the general trend of increasing particle length towards the tail end. The increase in particles length towards the tail end is more prominent for the jets formed by large angled conical cavities. The average length of particles in two experiments is shown by the dotted lines in “Fig. 4”. The average particle length decreases from 24 mm to 10.3 mm, when the jet strain rate is increased from $1.0\text{x}10^4 s^{-1}$ to $2.7\text{x}10^4 s^{-1}$. The average particle length measured in different experiments with the three metals is given in “Table 1”.

Table 1: Dynamic rupture strength of metals calculated from the experimental data of jet break-up.

Material	Strain rate at break-up $\dot{\varepsilon}_b$ (s^{-1} x 10^4)	Average particle length l_i (mm)	Static tensile rupture strength σ (Mpa)	Dynamic tensile rupture strength σ_f (Mpa)
Aluminium	1.4	10.57	90	549
	0.55	22		449
	0.41	32		486
Copper	2.0	5.9	200	1060
	1.7	6.8		1039
	1.26	9.6		1087
	1.02	13.2		1210
	0.81	17.8		1296
Mild Steel	2.07	8.3	450	1944
	1.9	8.1		1741

Table 2: A comparison of average dynamic tensile strength of copper calculated by different authors.

Mechanism of jet formation	Strain rate at break-up $\dot{\varepsilon}_b$ (s^{-1} x 10^4)	Dynamic tensile rupture strength σ_f (Mpa)	Reference
Hemi-spherical cavity collapse	1.0 – 4.0	1100	Mikhailov and Trofimov [2]
Shaped charge liner collapse	1.8 – 2.0	1200	Silvestrov and Gorshkov [8]
Conical cavity collapse	1.0 – 2.0	1100	Present studies

The dynamic tensile rupture strength of aluminum, copper and mild steel, calculated from eq. (10), is given in the last column of “Table 1”. It is seen that the average dynamic tensile strength of these metals is of the order of 500, 1100 and 1850 Mpa, respectively, which is nearly 5 times their static tensile strength. The dynamic rupture strength of copper calculated from the present data is compared with other similar studies and the results are given in “Table 2”. Though a different mechanism of jet formation is used still the results are in close agreement.

CONCLUSIONS

The measurement of length and velocity of the different particles of the particulated jet allows calculating the dynamic tensile strength of the jet material. The dynamic rupture strength of aluminium, copper and mild steel is nearly 4–5 times their static values. The results for copper have been compared with other findings and it has been concluded that the dynamic tensile strength at rupture is nearly 1.1–1.2 Gpa in strain rate region 10^4-10^5 s^{-1}.

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